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ANNUAL PROGRESS REPORT

A Virtual Environment for Manufacturing Systems
(ONR Grant No. N00014-92-J-4092)

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1. Productivity measures

Refereed papers submitted but not yet published: 0

Refereed papers published: 1

Unrefereed reports and articles: 2

Books or parts thereof submitted but not yet published: 0

Books or parts published: 0

Patents filed but not yet granted: 2

Patents granted: 0

Invited presentations: 1

Contributed presentations: 1

Honors received: 1*

Prizes or awards received: 0

Promotions obtained: 1**

Graduate students supported >= 25% full time: 9

Post-docs supported >= 25% full time: 0

Minorities supported >= 25% full time: 0

* M.J. Vanderploeg, ISU College of Engineering Research Excellence Award, August 1993
** James Oliver, from Assistant Professor to Associate Professor with tenure, April 1993

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2. Detailed summary of technical progress

Overview

The goal of this project is to build a theoretical framework to support the development of a virtual environment model of a computer-integrated manufacturing workcell to facilitate off-line programming, system simulation, and visual and analytical verification of actual system capabilities and performance. The research is divided into three complimentary thrusts, each of which emphasize the development and utilization of virtual environments, namely; assembly sequence planning, material removal process simulation, and off-line programming. The combined capabilities will form a first-generation virtual manufacturing workcell. The complete system will allow immersive user interaction with crucial parameters affecting system performance and provide rapid visual feedback.

During the past year, work has focused primarily on the theoretical foundations necessary to support virtual environments for manufacturing systems. The specific research progress on each of the three thrusts is summarized in the following paragraphs. As these activities have progressed, the facilities and infrastructure to support virtual reality (VR) applications at Iowa State have been continuously enhanced. In partial support of this project, the Iowa Center for Emerging Manufacturing Technology (ICEMT) purchased a Silicon Graphics Crimson Reality Engine workstation in the Fall of 1992. This is the premier graphics platform for advanced visualization applications. This was followed in Spring of 1993 with the purchase of a set of Crystal Eyes stereographic glasses, and a Logitech space mouse and tracking system with two sensors. This equipment has allowed us to implement preliminary virtual systems and experiment with our models and formulations. This Fall, the ICEMT has committed to the purchase of a second Reality Engine (an SGI Onyx), a FakeSpace Labs Boom3C high resolution color head-mounted display, and an assortment of hardware to support research in tactile force feedback. This will provide us with access to a truly state-of-the-art facility for VR development. From the point of view of this grant, the timing of these acquisitions is perfect. As the equipment is installed and debugged over the next several months, we will begin to implement our first fully immersive manufacturing environment.

In August 1993, Professor Lin-Lin Chen resigned her position as Assistant Professor of Industrial and Manufacturing Systems Engineering at Iowa State University to take a similar position at Taiwan Institute of Technology. Her work has focused primarily on the geometric issues related to assembly with particular emphasis on virtual environment applications. Although substantial progress was achieved on this front, the remaining PI's have elected to re-direct our assembly related thrust to investigate novel methods for force feedback to enhance sensory immersion for virtual assembly and other manufacturing related human-in-the-loop applications. With our encouragement, Dr. Greg Luecke, an Assistant Professor of Mechanical Engineering has submitted a proposal on this topic to replace the thrust led previously by Dr. Chen. We are currently awaiting word on the outcome of its review.

Assembly Planning Through Visualization

The research in assembly planning through visualization focuses on two problems: automated generation of assembly/disassembly plans for two-dimensional assemblies, and the automated computation of feasible disassembly directions for three-dimensional assemblies.

Assembly/disassembly plans for 2-dimensional assemblies - The goal of this research is the development and implementation of algorithms that can automatically generate assembly/disassembly plans from the geometric descriptions of components and from the adjacency relations among them. Basic algorithms, which determine if two components (or subassemblies) are locally and globally separable from each other, and the directions along which they can be separated, have been implemented. Assemblies that can be disassembled by removing one component at a time are called 1-separable. An algorithm that automatically generates a disassembly plan for 1-separable assemblies has been developed and implemented. For assemblies that require disassembling two or more components simultaneously, a strategy called onion peeling, which attempts to simultaneously remove several components with at least one external face, is currently been investigated. For all these applications, execution of the resulting assembly/disassembly plans are animated by using computer graphics.

Feasible disassembly directions for three-dimensional assemblies - The objective of this research is the development of an interactive computer graphics program for computing and visualizing globally feasible disassembly directions of a component. With such a tool, assembly/disassembly plans can then be generated interactively. Disassembly directions of a component can be computed from the sets of directions in which faces of the component are locally or globally visible. An algorithm for computing the set of directions in which a face is globally visible has been developed and part of this algorithm implemented. As computing global visibility is computationally expensive, preprocessing step that reduces that number of faces involved in the computation is desirable. One way is to compute the difference between a component and its convex hull, which results in a number of pockets. Only faces in the same pockets need be considered in the computation of global visibility. An algorithm for computing the difference has been implemented.

Off-line Programming and Visualization of Robots

Darren Knapp and Jim Troy are currently taking a lead role in the off-line programming effort. The first phase of this effort has developed an interactive environment for off-line programming of a single robot or two robots working together. This software enables the user to position the robot degrees of freedom or move the end effector directly using the mouse. This has been used to develop a robot program, down-load the program to a robot, and have the robot perform the programmed task. This software was written in Silicon Graphics GL. This new software enables modular installation of many robot types and other assembly equipment, and facilitates high speed graphics that are available using the Silicon Graphics Reality Engine in the Visualization laboratory. In addition, the user interface has been redesigned to accommodate interactive off-line programming of cooperating robots.

The second task was to evaluate the different programming environments for VR (Virtual Reality) applications. These included World Tool Kit, Performer, Inventor and GL. This evaluation looked at performance and portability issues. Currently we are implementing the robot off-line programming environment using GL and Performer.

Solid models of the manufacturing workcell at the Iowa Center for Emerging Manufacturing Technology have been developed to provide a virtual environment for evaluating off-line programming applications. Software has been developed to convert solid models generated in IDEAS and AutoCAD into the proper format for IRIS Performer. This will enable the use of existing models of the workcell's machines to be used directly in VR applications.

The software is first being modified to work in conjunction with the "Crystal Eyes" hardware. This will enable enhanced off-line capability by bringing 3D perception into the process. This should reduce the number of viewpoint changes and increase the overall efficiency of the off-line process. The next step will be to implement this software using the HMD that was recently ordered.

Simulation and Verification of Material Removal Processes

An algorithm has been developed for five-axis NC milling process simulation and dimensional verification. The algorithm employs a depth element (dexel) representation of the workpiece and milling tool to reduce the complexity of the solid representation and associated Boolean operations, and thus achieves high computational efficiency in milling simulation. Although in its original development, the dexel coordinate system is aligned with the screen space of a typical graphic viewing transformation, in this implementation the dexel coordinate system may be defined in an independent fashion. Objects in world space are scan converted into the dexel coordinate system and are then transformed into the screen space for display. Five-axis NC milling simulation is performed by continuously subtracting the dexels of an arbitrarily oriented milling tool from those of a workpiece. Rather than computing the precise yet complex tool swept volume, the simulation process introduces instances of tool motion to describe the typical five-axis motion, i.e., each tool motion is discretized into several instances so that adjacent instances are at most one dexel apart. Thus, the computational expense of scan converting tool swept volumes is eliminated while the accuracy and efficiency of the simulation are retained.

Discrete dimensional verification is performed simultaneously with the milling simulation process to compute the milling error between the milled surface and the design surface. This discrepancy is computed as the distance between each exposed dexel and the design surface(s). Levels of color depict the severity of milling error on the workpiece so the verification result precisely reveals the quality of tool paths. The combined simulation and verification algorithms provide computational efficiency sufficient to run industrially significant examples in real time on a relatively inexpensive workstation. This verification algorithm is unique in several other respects. First, the verification result is displayed on the finished workpiece, not the design surfaces, hence it provides a realistic depiction of the actual process which is helpful for determining tool path modifications and additional finishing processes. Secondly, milling error is computed only at dexels updated during simulation, thus the number of points to be verified is culled automatically.

In addition to the research in NC milling simulation, work on geometric simulation of the press forming process was supported partially during the spring and summer. This research is aimed at providing surface and die designers with an alternative to non-linear finite element analysis in the preliminary design stage. The algorithm developed provides an efficient qualitative assessment of parts produced by press forming. Based on a model of the formed surface, the system "un-forms" the model using a geometric transformation that conserves area. This provides an accurate assessment of the blank shape and material distribution which is useful for die and binder wrap design. In addition, distortions of the mapped blank grid indicate potential forming problems such as tearing or wrinkling. This work is primarily the Masters research of Mr. Nirmal Nair. Unfortunately, after spending the summer on ONR support continuing this research, Mr. Nair elected not to pursue his Ph.D. degree.

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3. Lists of publications

Fay Gau, "Global Visibility Computation for Automated Machining", Master's Thesis, Department of Industrial and Manufacturing Systems Engineering, Iowa State University, 1993

Nirmal K. Nair, "Development of Manufacturability Constraints for Press Forming of Sheet Metal Components," Master's Thesis, Department of Mechanical Engineering, Iowa State University, 1993

Nirmal K. Nair and James H. Oliver, "An Area Preserving Transformation Algorithm for Press Forming Blank Development," *ASME Advances in Design Automation*, DE-Vol. 65-1, pp. 163-172

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4. Transitions and DoD interactions

We have initiated an interaction with Grumman Corporate Research Center regarding our work in press forming simulation and assessment. So far this relationship has explored the applicability of our approach to actual forming problems at Grumman. Grumman has supplied data of typical parts with relatively simple geometry, yet which have experienced forming problems on the shop floor. We are currently adapting our method to accept this data. Our preliminary results are very encouraging, and we look forward to sharing some exciting results with Grumman soon.

Last spring, Grumman asked Dr. Oliver to participate on a team proposal to Wright-Patterson Air Force Base to develop a comprehensive forming assessment tool. Our proposal survived into the final round, but ultimately, was not funded. Additional discussions this spring involved a possible collaboration between Grumman, Alcoa, and Iowa State on an ARPA TRP proposal focusing on advanced forming processes. However, after preliminary discussions with federal contacts, we elected not to go forward with a proposal.

In April, Dr. Oliver presented an invited seminar at the University of Washington, and visited the Human Interface Technology (HIT) Laboratory there. Several discussions about our mutual interest in VR applications took place. In May Dr. Oliver attended an ONR Workshop on VE for Training, Targeting and Teleoperation at Research Triangle Park, NC. As part of this workshop, he toured the VR laboratory at the Computer Science Department of the University of North Carolina. In June, our research team prepared a videotape submission for the Navy Scientific Visualization and Virtual Reality Seminar at the Carderock Division of the Naval Surface Warfare Center. Unfortunately, our submission was not selected for inclusion in the conference.

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5. Software and hardware prototypes

Assembly/disassembly plans for two-dimensional assemblies: Algorithms for detecting whether components are locally separable and globally separable have been implemented on Silicon Graphics workstations using the FORMS user interface.

Feasible disassembly directions for three-dimensional assemblies: Algorithms for computing the global visibility map of a face with respect to another face on the component have been implemented on Silicon Graphics workstations using the FORMS user interface. The resulting global visibility map and the given component are displayed. This program has great potential for commercialization as the resulting global visibility maps are not only useful in assembly planning but also in generating probe paths in coordinate measurement and in generating cutter paths in numerical controlled machining. Algorithms for computing the difference between a component and its convex hull have also been implemented. The convex hull of a component is computed by using the programs *alvis*, *detri*, and *mkalf* developed by Herbert Edelsbrunner of University of Illinois at Urbana-Champaign. As limited by the requirement of this convex hull program, the given components are assumed to have integer coordinates.

Off-line programming software for industrial robots: This program is written in IRIS GL for Silicon Graphics workstations. Users can define the path and function of a robot in its work space in an interactive graphics environment. Programs are then transferred to NC machine code and can be downloaded to run the actual machine.

NC milling simulation with dimensional verification: This system is implemented on the Silicon Graphics platform using IRIS GL. The software input includes design surface geometry in IGES format, raw stock geometry, CL-file, tool geometry, milling tolerances, dimensional verification range, and desired dimensional resolution. The program operates in two modes. In simulation mode output is a realistic, smooth and continuous animation of the milling process. Verification mode augments the simulation by color-coding the machined part as it approaches the designed surface to highlight its deviation from the design surface. Additionally, the machined workpiece can be rotated and viewed from any desired vantage point. The Iowa State University Research Foundation (ISURF) has applied for a patent on this technology and has recently signed a license agreement with Arete Software Corporation, a high technology start-up company in Ames, Iowa. ISURF has also applied for a patent on our algorithms for press forming assessment. Arete Software has signed an option agreement with ISURF for this technology.